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OPTIMIZATION OF THE TECHONOLOGICAL PARAMETERS IN THE MILLING PROCESS

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Abstract: *In this article is proposed and tested a new optimization model of the milling process on the CNC centers. The optimization model includes a real time optimization algorithm of the technological parameters, cutting speed and feed rate which can be implemented with minimum costs on the industrial CNC milling machines.* ***Key words:*** *optimization, CNC machining center, feed rate, cutting speed.*

1. INTRODUCTION

Knowing the fundamental principles of NC programming stated in [9] we can conclude that the milling process can be optimized. The optimization process consist in determining of the technological parameters like feed rate, cutting speed and cutting depth using specific algorithms, so we can replace the classic procedure that uses tables in their computing.

Optimization focuses on improving the precision and the surface finishing [15], in the decreasing of milling time [2] and milling costs or in increasing the time life of the cutter [4]. The milling process optimization in real time was studied in [8]. A mathematical optimization method involves the independent and dependent variables set and the definition of the restrictions and objective function. For objective function we impose the maximum or minimum condition. This type of optimization is described in articles [14].

Analytical methods of optimization are detailed in articles [1], [6]. Within these models are established relationship of dependency between milling power, the cutter durability, surface roughness, the costs of processing and milling technological parameters like: feed rate, cutting speed and depth of milling.

In an effort to determine the optimal values for the milling process, lots of models were developed according to the considered objective functions: minimizing production cost [7], minimizing production time [2], maximizing processing speed [13] or profit maximization [5].

2. THE OPTIMIZATION MODELS APPLICABLE TO THE MILLING PROCESS

Optimization models are defined by objective function: minimizing production cost, production time is minimized, maximize processing speed, or maximize profits. In [3] are presented optimization models having as objective function the cost of processing, the minimum and maximum profit production.

2.1 Optimization model having the objective function the unit cost of finished product

Depth of cut, feed rate and cutting speed has the greatest effect on the processing operations. Therefore, in practice only be taken into account these parameters. Depth of cut is usually predetermined by the geometry of work piece and the sequence of operations. It follows that the processing is done at the appropriate depth by making a single pass operation so that processing time is minimized. This does not mean a minimal cost. It was further assumed that the processing required depth is reached through a single pass. The problem of determining the optimal parameter combination is reduced to determining the feed speed and cutting speed. Unit cost of the finished product has the general representation:

$$C_u = C_s + (C_o + C_i)t_S + (C_o + C_i)t_L + (C_o.t_{tc} + C_t + C_i.t_{tc}).\left(\frac{t_L}{T}\right) \quad (1)$$

$$t_L = \left(\frac{L}{w}\right) \quad (2)$$

where:

C_i - indirect manufacturing costs
C_o- costs due to cost human operator
C_s - work piece cost
C_t - the cutter cost
C_u - the unit cost the product
L - overall length for milling
T - the durability of the cutter
t_L - the necessary time to cut the L distance
t_s - machine adjustment time
t_{tc} -the necessary time to change the cutter
w - feed rate

According to equation (1) unit cost is given by four terms: material cost, the cost of the CNC milling machine setup, the effective cutting cost and the cost due to change tools. In the milling operation the necessary time to cut the L distance is expressed:

$$t_L = \left(\frac{L}{s_d.z.n_{ap}}\right) \quad (3)$$

where:

n_{ap} - main shaft speed
s_d - the advance per tooth
z - number of teeth of the cutter

For further calculations we need the cutting speed expression. This was deduced in [7] and has the form:

$$v = \frac{C_v.\left(\frac{t_d}{5.s_d}\right)^{g_1}}{S_a^{g_2}.\left(\frac{T}{60}\right)^{g_3}} \quad (4)$$

where:

C_v - constant associated to the cutting speed associated
g_1 - milling depth associated exponent
g_2 - sectional area associated exponent
g_3 - exponent associated with the durability of the cutter
v- cutting speed
S_a - cross-sectional area of the chip

The value of the constant C_v and the value of the g_3 exponent depend on the cutter material and on the hardness of the processed material. For a given work piece, a high quality cutter means a greater value for C_v constant. In this model, for high speed steel cutters made of HSS, g_3 exponent can take the value 0,15 while when tough alloy steel are used then g_3 can increase up to 0.30. The durability of the cutter according to the cutting speed is:

$$T = 60.\left[\frac{C_v.\left(\frac{t_d}{5.s_d}\right)^{g_1}}{S_a^{g_2}.v}\right]^{\frac{1}{g_3}} \quad (5)$$

This expression corresponds to the case where a single tooth cutter is always in the work piece. In general, in the milling operation are used cutters with more teeth. If, at some point in the work piece are multiple teeth, each tooth will be in contact only a fraction of the total time T.

2.2 The optimization model having as objective function the time milling unit

We define the time milling unit T_u for processing the work piece on a CNC milling machine in the form:

$$T_u = t_s + C_3.v^{-1}.s_d^{-1} + t_{tc}.C_3.v^{\left(\frac{1}{g_3}-1\right)}.s_d^{\left(\frac{g_1+g_2}{g}-1\right)} \quad (6)$$

where C_3 is a time constant associated with sustainability cutter.

This time is the sum of times for adjustment, change processing tools and the actual processing of the work piece. Since the time machine and time to adjust and to change cutters are not influenced by processing parameters they can be excluded from the optimization model.

3. FORMULATION OF RESTRICTIONS IN THE OPTIMIZATION PROBLEM

In the milling process the restrictions apply to the cutting speed, feed rate and depth of milling. They are determined by the effective power to the main shaft, maximum speed, the maximum force in the tool holder, maximum heat generated in the milling process that can be dissipated by the spindle, tool holder and cutter, the rigidity milling machine and the degree of roughness required.

3.1 The restriction imposed by the main shaft motor output power

The motor output power developed at the main shaft of the milling machine determines the maximum diameter of the cutter. Considering that the economic factor is decisive it is intended that in the milling we use a high percentage of maximum power. In [12] was proposed the following expression for the power of cutting:

$$P = \frac{0{,}78.K_p.C_f.t_d.t_1.z}{60.D.\pi.\eta}.v.s_d^{0{,}8} \tag{7}$$

where:

C_f - cutter wear factor

K_p - specific power milling

t_l - milling width

t_d - milling depth

This power must not exceed the maximum power developed by the main shaft motor of the milling machine. The restriction is written as:

$$P \le P_{\max} \tag{8}$$

where $P_{\max}$ is the maximum power of the motor of main shaft.

3.2 The restriction imposed due to the degree of surface roughness milled

If finger-type milling cutters are used during the process, the surface roughness is given by:

$$R_a = \frac{318.s_d^2}{4.D} \tag{9}$$

where: R_a - surface roughness.

The roughness R_a obtained after the milling operation, should not exceed a maximum degree of finish $R_{a\max}$ certified by the manufacturing specifications of the final product. This limitation reflects a new restriction which has the form:

$$R_a \le R_{a\max} \tag{10}$$

3.3 The restriction imposed by the maximum force developed during milling

The cutting force that occurs during milling is due to the feed movement and to rotating movement of the cutter. Module of this force is:

$$F_a = \sqrt{F_t^2 + F_n^2} \tag{11}$$

where:

F_a - the resultant milling force

F_n - the axial component of the milling resultant force

F_t - the tangential component of the milling resultant force

The resultant milling force F_a, should not exceed the maximum force that is specified by the manufacturer of the milling machine,$F_{a\max}$. :

$$F_a \le F_{a\max} \tag{12}$$

The value of maximum force that can withstand the cutter is specified by the manufacturer and is determined experimentally under conditions specified so that the milling process can be done safely.

4. FORMULATION OF REAL TIME OPTIMIZATION ALGORITHM

The technological parameters which are to be optimized are the feed rate and the cutting speed. Also the influence factors are taken into account like the milling depth and milling width. Usually, these parameters are calculated in a very conservative manner and are tabulated in manufacturer's cutter catalogs and eventually limited by the milling machine manufacturer specifications in the manual for its use.

The stiffness of the spindle - tool holder - cutter assembly along with the work piece clamping system on the table affects the frequency, amplitude and damping vibrations during milling. A detailed analysis of the main shaft spindle - tool holder - cutter assembly behavior due to used bearings according is described in [14]. The behavior of the main shaft due to elasticity induced by spindle - tool holder - cutter is studied in [10].

It follows a second type of limitation and selection of feed rate, cutting speed and cutting depth in milling process. The limitation applies not only to the maximum and minimum feed rate and cutting speed but also to the sub domains of these intervals in which the milling is stable, separated by sub domains where the milling is unstable.The milling is unstable when it is accompanied by maintained vibrations whose amplitude increases progressively.

The offline information refers to domains of allowed spindle speeds and permitted domains for the milling depths. These domains are obtained from experimental modal analysis of the main shaft - tool holder - cutter and stability diagrams. The online information refers to physical quantities that characterize in real time the milling process. The first physical quantity of interest is the electric currents in the main shaft motor controller, respectively the power dissipated by this controller, P_{cm}. For this power we will try to determine the dependency type:

$$P_{cm} = P_{cm}(t_d, w, s_d) \tag{13}$$

The second physical quantity considered is the intensity of acoustic emissions, I_S, produced by the cutter during milling the work piece. For this we determined a dependency type:

$$I_S = I_S(t_d, w, s_d) \tag{14}$$

4.1 Establishing the objective function and restrictions in the optimization problem

The proposed objective function is the total amount of metal chipped in an equal time with the cutter durability. The general optimization problem is as follows:

For the milling machine CNCx and
the milling cutter of type CUTTER x and
the work piece of type WORKPIECE x and
the operation of type MILLING x
COMPUTE the values [v, w, t_d] leading to the MAXIMUM $MAX(Q.T)$ (15)

with the restrictions:

$$n_{ap-\min} < n_{ap-optim} < n_{ap-\max} \tag{16}$$

$$w_{\min} < w_{optim} < w_{\max} \tag{17}$$

$$t_{d\min} < t_{doptim} < t_{d\max} \tag{18}$$

$$P_{cm} \le P_{\max} \tag{19}$$

$$n_{ap-optim} \in [n_{ap1,} n_{ap2}] \tag{20}$$

$$n_{ap-optim} \in [n_{apk,} n_{apk+1}] \tag{21}$$

$$n_{ap-optim} \notin [n_{ap2,} n_{ap3}] \tag{22}$$

$$n_{ap-optim} \notin [n_{apk-1,} n_{apk}] \tag{23}$$

$$t_{doptim} \in [t_{d1,} t_{d2}] \tag{24}$$

$$t_{doptim} \in [t_{dk,} t_{dk+1}] \tag{25}$$

$$t_{doptim} \notin [t_{d2,} t_{d3}] \tag{26}$$

$$t_{doptim} \notin [t_{dk-1,} t_{dk}] \tag{27}$$

$$P_{em} \in [P_{cm}(t_d, w, s_d) - \Delta_1, P_{cm}(t_d, w, s_d) + \Delta_1] \tag{28}$$

$$I_S \in [I_S(t_d, w, s_d) - \Delta_2, I_S(t_d, w, s_d) + \Delta_2] \tag{29}$$

where:
n_{ap} - spindle speed
n_{ap0} - initial spindle speed
$n_{ap-optim}$ - the optimized spindle speed
n_{ap-k} - the spindle speed delimiting the stable milling process of the unstable milling process
n_{ap-max} - the maximum spindle speed
n_{ap-min} - the minimum spindle speed
P_{em} - the instant electrical power dissipated by the controller measured during milling process
t_{di} - the milling depth for milling process named
t_{dk} - the milling depth delimiting the stable milling process from the unstable domain
t_{d-max} - the maximum milling depth
t_{d-min} - the minimum milling depth
$t_{d-optim}$ - the optimum the milling depth
Δ_1 - the maximum admitted fluctuation of the dissipated power of the spindle motor controller
Δ_2 - the maximum admitted fluctuation of the acoustic emission intensity
Q - the productivity of the process expressed in mm^3/min

The restrictions (20) - (27) are due to the dynamic behavior of milling machine and are obtained from experimental modal analysis using the stability diagrams. The restrictions (28) and (29) are determined experimentally for each type of milling machine, cutter, work piece and milling process and shall constitute as a database. For a general milling operation, we chose from this database the nearest appropriate values that will be compare with data obtained from sensors and adjusted in real time.

5. IMPLEMENTATION AND VALIDATION OF THE ALGORITHM

The optimization algorithm was implemented on the experimental stand shown in figure 1 and figure 2 by modifying a FUS 22 CNC milling machine, two IBM PC AT compatible computers, a microphone, a digital ammeter and related software.

In order to calibrate the optimization algorithm we performed two sets of experiments so that we can highlight the transition from the stable process to the unstable domain by excessive growth, nonlinear of the milling power and acoustic emission intensity.

Fig. 1 The FUS 22 CNC milling machine

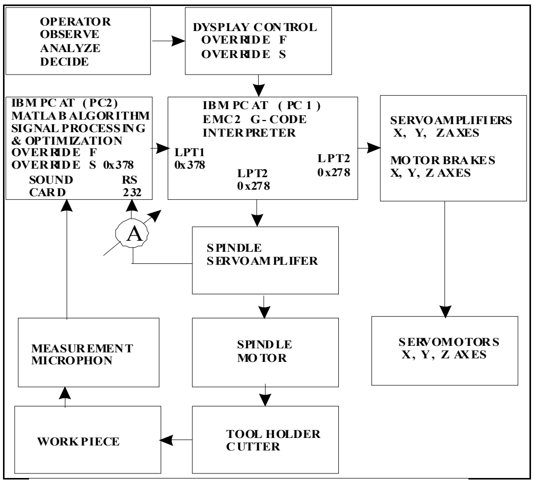

Fig. 2 The block diagram of experimental stand

The experiments consisted in the milling of straight channels with Kennametal cutters in an OL 52 steel work piece. During the milling operation was measured the intensity of acoustic emission and the intensity of electric current through main shaft motor driver. Experimental data for each experiment were separately stored as ASCII files on the computer PC2 process. They allowed the deduction of equations (14) and (15).In the first set of experiments was performed milling at constant speed and variable feed rate in 100% - 200% relative to the milling machine book values. The variation domain was chosen as specified in [6]. In the second set of experiments was carried out the milling at constant feed rate and variable speed in the 100% - 80% domain, relative to the milling machine book values. The theoretical power dissipation according to [15] is :

$$P_{et}(n_{ap},w)=P_g+\frac{K_P.s_d.z.n_{ap}.t_d.t_1.C_f.A_1.\left(\frac{w}{z.n_{ap}}\right)^{B_1}}{\eta_{lc}} \qquad (30)$$

where:

P_{et} - the total electrical

P_g -the electrical power when idling

A_1-associated coefficient to the cutting forcene

B_1- associated coefficient to the axial force

η_{lc} - the milling machines overall efficiency

For the FUS 22 CNC milling machine the theoretical power dissipation (35) becomes:

$$P_{et}(t_d,t_1,n_{ap},w)=95+0{,}04797.w.t_d.t_1.\left(\frac{w}{z.n_{ap}}\right)^{-0{,}19633} \qquad (31)$$

According to [13] and to the experimental data, the cutter durability is :

$$T_i(n_{api},w_i)=\left[17{,}3+60{,}7.\exp\left(\frac{-w_i}{0{,}14.n_{api}}\right)+16{,}2.\exp\left(\frac{-w_i}{2{,}1.n_{api}}\right)\right]+ \qquad (32)$$

$$+\left[17{,}3+60{,}7.\exp\left(\frac{-w_0}{0{,}14.n_{ap0}}\right)+16{,}2.\exp\left(\frac{-w_0}{2{,}1.n_{ap0}}\right)\right].\left[\left(\frac{n_{ap0}}{n_{api}}\right)^{1{,}8}-1\right]$$

where:

w_0 - initial feed rate

w_i - optimized feed rate

In order to verify the optimization algorithm the feed rate variation was restricted to 100% -130% while the spindle speed was restricted to 100% - 94% relative to the milling machine book values. Using the evaluation in real-time of the milling power consumption and the intensity of the acoustic emissions the closed-loop system detects the inappropriate fluctuation and makes the necessary corrections to the feed rate and to the spindle speed. In table 1 are presented the experimental results, the objective function T.Q corresponding to the optimized milling process versus no optimized process T_0Q_0.

Table 1.

The results of milling experiments

Kennametal cutter D(mm)	Feed rate	Spindle speed	Objective function $T.Q/T_0Q_0$
6	$w=1{,}3.w_0$	$n_{ap}=n_{ap0}$	1,22
6	$w=w_0$	$n_{ap}=0{,}94.n_{ap0}$	1,11
8	$=1{,}3.w_0$	$n_{ap}=n_{ap0}$	1,20
8	$w=w_0$	$n_{ap}=0{,}94.n_{ap0}$	1,10
10	$w=1{,}3.w_0$	$n_{ap}=n_{ap0}$	1,11
10	$w=w_0$	$n_{ap}=0{,}94.n_{ap0}$	1,10
12	$=1{,}3.w_0$	$n_{ap}=n_{ap0}$	1,17

12	$w=w_0$	$n_{ap}=0,94.n_{ap0}$	1,10
14	$=1,3.w_0$	$n_{ap}=n_{ap0}$	1,16
14	$w=w_0$	$n_{ap}=0,94.n_{ap0}$	1,09

VI. Conclusions

The analysis of the data presented in Table 1 show that the proposed objective function QT increase by changing the feed rate or cutting speed. Minimum percentage increase of the objective function is 9%, corresponding to 16 mm diameter of the cutter while we can reach 22% increase of the objective function for 6mm diameter cutter. Optimization algorithm has been validated. It can be improved both in the design, using a neural network as well as in the implementation process by replacing the computer process PC2 with a dedicated microcontroller.

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OPTIMIZAREA PARAMETRILOR TEHNOLOGICI DE FREZARE

Rezumat: *În acest articol este propus un nou model de optimizare a operaţiei de frezare efectuată pe centrele de frezare CNC. Modelul de optimizare include un algortim de optimizare în timp real a parametrilor tehnologici de frezare, viteză de aşchiere i viteză de avans care poate fi implementat cu costuri minime pe maşinile de frezat industriale.* ***Cuvinte cheie:*** *optimizare, centru de prelucrare CNC, viteză de avans, viteză de aşchiere.*

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